Operation and Maintenance of the Wasatch Front, Utah, GPS Network (Monitoring, Upgrades, Data Recording and Processing)

Part of the University of Utah EBRY (Eastern Basin Range-Yellowstone) GPS Network

Annual Report for Period
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I. Summary of Investigations Undertaken

Under this USGS National Earthquake Hazard Program project, the University of Utah conducted research focused on the operating the Wasatch Front GPS network, data processing of permanent and campaign GPS stations focused on monitoring the surface deformation of the populated Wasatch Front area, Utah, and evaluating the effect of paleo- and historic earthquakes on the crustal deformation field from viscoelastic modeling. High-resolution GPS data, acquired by 20 continuous stations and seven field campaign surveys of ~ 60 stations, were integrated with other earthquake source data, including paleoearthquakes, fault-loading rates and historic seismicity, to evaluate the earthquake hazard of the Wasatch fault.

Continuous and Campaign GPS Observations -- Our main field project included the operation and maintenance of seven University of Utah continuous GPS stations, including the installation of a new GPS station in the Wastach fault footwall at Alta, Utah (HWUT) summer of 2005 (ALUT, Figure 1). Our CGPS data are transmitted daily to the UNAVCO archive center and are web accessible to any user in near-real time (http://archive.unavco.org/query/pss).

Moreover, we processed the data from seven GPS campaign field surveys along the Wasatch fault in 1992-1995, 1998, 2000, and 2003 to update the contemporary velocity and strain field of the Wasatch fault. Our latest results indicate that the Wasatch fault and subsidiary faults has notably higher ground deformation rates than expected from Holocene geologic data that increases the earthquake hazard from previous estimates.

Data Processing -- We also finished developing automatic GPS data processing of 29 stations in the north and central area of Utah, encompassing the Wasatch fault, that include eight stations from the University of Utah, five from the BARGEN CGPS array, twelve from the EarthScope PBO network, and four from other cooperative CORS stations (Continuously Operating Reference Station of the Nation Geodetic Survey (NGS). Our processing scheme uses precise (final) GPS orbit data acquired from International GPS Service (IGS), that are available with a 12-day latency. With this scheme the Wasatch fault GPS time-series are automatically updated weekly using the past two weeks precise orbit data. The resulting processes GPS data are posted on our website at http://www.mines.utah.edu/~ggcmpsem/UUSATRG/GPS/time_series.html.

Contemporary Loading Rates of Wasatch Fault from GPS Data -- We used the resulting GPS data to determine the contemporary crustal loading rates of the Wasatch Front area based on the derived horizontal velocity field. We then employed an elastic dual-dislocation fault simulation to estimate the fault-loading rates and related elastic parameters. This model assumes loading of the fault is taking place beneath the locked-upper crust containing the elastic controlled Wasatch fault, or at depths beneath the seismic locking depth of ~10 km. Our results show that the loading rates are 5-6 mm/yr on a west-dipping, ~30°, creeping zone that is about a factor of 2 to 3 higher than the geological fault-slip rate of the Wasatch at the surface. The high loading rate of this system, if assuming all of the stress is concentrated on the seismogenic fault, implies a higher earthquake ground-shaking hazard from the fault compared with that calculated only by historic seismicity and paleoearthquake data.

Post-Seismic Deformation of the Wasatch Front -- Viscoelastic relaxation of prehistoric (M>7) and historic (M>5.6) earthquakes were evaluated to examine time-dependent effects of past earthquakes on the contemporary strain field. We first examined the postseismic deformation caused by the 1959 M=7.5 Hebgen Lake, MT, earthquake, a large, scarp-forming rupture that is the only historic normal-faulting event in the world with the recorded post-seismic relaxation history recorded by a variety of geodetic and seismic methods. Because this event is the only large normal-faulting event in the Basin-Range with time-dependent crustal deformation data, we used it as a proxy for time-dependent behavior that would be expected on the Wasatch fault. Geodetic data for the Hebgen Lake earthquake include GPS, precise leveling and EDM acquired over the ~45 year post seismic period. This event thus provides a unique source of information on the viscoelastic behavior and rheology that is crucial to inter-seismic modeling of similar faults such as the Wasatch fault. Our viscoelastic modeling results of the Wasatch fault using a modified rheology model from the Hebgen Lake earthquake demonstrate that there is ≤0.1 mm/yr of horizontal motions from the are negligible compared to the 1-3 mm/yr of E-W extension measured by GPS in the Wasatch Front area.

Integrated Earthquake Hazard -- Various earthquake sources and recurrence models contribute differently to the probabilistic earthquake hazard estimations. The Wasatch Front seismic, geologic, paleoearthquake, and GPS data were included in a study to evaluate the probabilistic ground-shaking hazard for a specific location in Salt Lake Valley. Results demonstrate the usefulness of integrating all available data for a more complete estimate of earthquake hazard for the entire region.

II. Results (October 1, 2004 to September 30, 2005)

General Accomplishments -- Under this project, the University of Utah received support to assess earthquake hazard on the Wasatch Front, Utah using continous and campaign high precision GPS measurements and investigating inter-seismic models of normal fault behavior applied to the Wasatch fault. Because of reduced funding from our initially proposed project, tasks were reduced to three elements: 1) installing one new continuous-GPS (CGPS) sites in the central Wasatch fault area, maintenance of seven CGPS sites on the Wasatch Front, and incorporating CGPS data from five stations of BARGEN northern Basin-Range array, twelve of the newly installed EarthScope PBO stations in northwestern Utah, and four sites recorded as part of the CORS network. This provides a total of 29 continuous GPS stations in our processing scheme; 2) Evaluating the effects of viscoelastic relaxation of prehistoric (M>7) and historic (M>5.6) earthquakes to evaluate time-dependent effects of past earthquakes on the contemporary strain field of the Wasatch Front; 3) Estimating the loading rate of the Wasatch fault based on the horizontal velocity field from GPS data using a dual-dislocation fault models to best simulate the hypothesized three-dimensional Wasatch fault geometry; and 4) Evaluating the contributions of various seismic sources and fault scenarios to the probabilistic ground-shaking hazard for a specific location in Salt Lake Valley. These incorporated the Wasatch fault seismic, geologic, paleoearthquake, and GPS observations

Specific efforts included:

- Operating and maintaining eight permanent GPS stations (Figure 1). In summer 2005 we installed one new GPS station ALUT at Alta, Utah, which was installed in the footwall of the Wasatch fault. (Figure 1). Note that this site is in the immediate vicinity of the Wasatch fault footwall-block near Salt Lake City to assist with monitoring ground motions along this most populated part of the Wasatch Front. This site was installed on a 20' steel towers erected on bedrock, and have solar power and transmit data in real-time to a University of Utah seismic station at the Alta town office. Importantly this site was a cooperative project between the University of Utah and the Alta Ski Lift Corp who allowed and assisted us with installation on one of their large steel towers.

- Reconnaissance for an additional GPS sites on the hanging-wall block of the southern Wasatch fault have been completed. This station is needed to provide deformation information on the lateral E-W extension of the Nephi segment of the fault. The new site will require a telemetry repeater to link to our installed transmission system. Site reconnaissance and permitting of this site was begun summer 2005.

- Automatic processing data was routinely is being done for 60 CGPS stations in the Intermountain region, including 29 in the Wasatch Front and 31 around the Yellowstone-Snake River Plain area. Updated time series of these stations are posted on our website: http://www.mines.utah.edu/~ggcmpsem/UUSATRG/GPS/time_series.html.

- Daily downloads of our CGPS data are automatically transmitted to the UNAVCO data archive for web access to any interested user at http://archive.unavco.org/query/pss.

- University of Utah GPS data, including the Wasatch fault array, are described along with processed time series and relative crustal motion vectors on our website http://www.mines.utah.edu/~rbsmith/RESEARCH/UUGPS.html

- Modeling the GPS data was investigated using linear and non-linear inverse methods to determine the geometry and rates of causative faults especially incorporating the 3D geometry of the Wasatch fault.

- Completing our paper on the viscoelastic modeling of lithospheric rheology beneath the Hebgen Lake fault zone in Montana and evaluating postseismic deformation of the Wasatch Front, Utah. This paper was submitted to the Journal of Geophysical Research and is under review.

- Presented invited and contributed papers on our research at the following scientific meetings: 1) the 2004 fall meetings of the American Geophysical Union; 2) the 2005 EarthScope meeting, and 3) the 2005 annual meeting of the Geological Society of American.

- Organized and assisted the effort to include the northern Basin-Range, including the Wasatch fault, as a major element of the Plate Boundary Observatory. The research objective is to focus on the physics of earthquakes as well as an example of GPS monitoring of an active fault with major societal impact. The University of Utah has assisted PBO engineers with sitting and permitting issues for their sites in northern Utah. New PBO sites are included in the Figure 2.

Wasatch Front Continuous GPS (CGPS) Operation

The Wasatch Front CGPS network began operating for eight years (1997-present) from a skeleton 3-station network to an 8-station array. Our eight continuous GPS sites (Figure 2) are designed to operate in high mountainous, cold weather environment planned for reliable unattended operation. Spread spectrum digital radio links to the University of Utah campus transmit the GPS data which are then recorded on a Sun UltraSparc computer. Data are sampled at a 30-second rate.

The instrumentation for our GPS networks is provided in an online form documenting the engineering and operating parameters of our stations. This information is accessible in two documents:

1) http://www.mines.utah.edu/~rbsmith/RESEARCH/UUGPS.html

2) http://www.mines.utah.edu/~rbsmith/RESEARCH/CGPS_summary.html

Automatic processing of the Wasatch Front CGPS data uses the Bernese Processing Engine of the new Bernese 4.2 software. Our automatic data processing scheme uses the precise (final) GPS orbit data from NGS that are available weekly with a two-week delay. The time series of the total 60 CGPS stations (including 31 of the Yellowstone-Snake River Plain network) are thus updated every week to the past two weeks and posted on the website: http://www.mines.utah.edu/~ggcmpsem/UUSATRG/GPS/time_series.html.

Coordinate solutions are saved in SINEX-formatted files that can rigorously be combined with solutions determined by other institutions using different processing software.

Problems Encountered – We encountered no major logistical problems during the report period except the extended negotiations of permitting the Alta site due to strict environmental requirements and engineering specifications required.

III. Research Results

During the report period we evaluated various processing schemes to incorporate the best reference frame. Multi level tests of updated reference for our non-uniform 2-D velocity field with respect to the stable North America reference frame was best employed by ITRF2000, International Terrestrial Reference Frame 2000 (Figure 3).

Processing all of our data, from the beginning of our GPS studies in 1995, in this framework revealed that strain is negligible east of the Wasatch fault, but increases rapidly west of the fault to a principal component of E-W extensional strain at ~ 0.024 ± 0.006 μstrain/yr, corresponding to a velocity of 1.6 ± 0.4 mm/yr a 65-km wide area spanning the fault. This rate is comparable to that from the earlier campaign surveys, that showed a regional horizontal strain rate of 0.049 ± 0.023 μstrain/yr corresponding to a velocity of 2.7 ± 1.3 mm/yr across 55-km wide area spanning the Wasatch fault (Martinez et al., 1998). Baselines that cross the fault also show an increase of strain from south to north, corresponding to a change of 1.8 to 2.6 mm/yr. These spatial variations imply that local tectonic strain is heterogeneous in both NS and EW directions.

Viscoelastic Modeling for Postseismic Deformation of the Wasatch Front

To investigate viscoelastic behaviors associated with large normal-faulting earthquakes, we first modeled the lithospheric structure by employing the post-seismic deformation field recorded by geodetic measurements across the aftershock and fault zone of the M7.5 Hebgen Lake MT earthquake. Our work has evaluated simple rheological models that include two layers, an elastic layer on the top of a viscoelastic layer, and a viscoelastic half space. Results revealed that the lithosphere is stronger near the Hebgen Lake fault zone, and weaker in the vicinity of the Yellowstone caldera with much higher heat flow and a thinner brittle crust (Figure 4). These models also imply a more viscous lower crust than the upper mantle, in agreement with a corollary that the continental mantle has relatively small long-term stress.

We then employed the derived HEBGEN model (Figure 4) to evaluate the postseismic deformation of a much larger area of the Intermountain region produced by the Hebgen Lake and the 1983 M_s=7.3 Borah Peak, ID earthquakes. The results suggest that the postseismic relaxation of these earthquakes produced horizontal ground motions up to ~2 mm/yr that must be considered for intraplate kinematic models (Figure 4).

Furthermore, our HEBGEN model is similar to a viscosity model based on observations of the Late-Quaternary loading and vertical rebound of the Quaternary Lake Bonneville of the eastern Basin-Range Province (Figure 5). We thus employed both models to evaluate postseismic ground motions associated with six most recent, <1.5 ka, Holocene paleoearthquakes and three large, M≥5.6, historic earthquakes of the Wasatch fault zone, UT. These results demonstrate ≤0.1 mm/yr of contemporary horizontal motions induced by these earthquakes, which are negligible compared to the ~1-3 mm/yr of E-W extension determined by GPS measurements (Figure 5). This study provides new insights into the widespread effects on regional deformation from postseismic relaxation of large earthquakes that should be considered in kinematic models and earthquake hazards of intraplate tectonic regions.

Elastic Modeling for Fault Geometry Using GPS Measurements

Using the horizontal deformation results from the CGPS and the campaign GPS surveys, we ran various tests of nonlinear inversions on fault geometry and loading rates. Before doing this, we first estimated and removed the background tectonic motion, namely the extension of the eastern Basin and Range from our observed velocities, to obtain the motion caused only by the loading of the Wasatch fault. Moreover, the fault length was fixed to 350 km, the total length of the geologically mapped Wasatch fault, that is long enough to avoid the dislocation edge effect. Results for the Wasatch fault suggest a best fit to the GPS data by a fault plane with a width of 23 km, a strike of N4ºW, a dip of 27º beneath a seismogenic zone beginning at a locking depth of 9 km, and with a fault loading rate of 7 mm/yr that is notably higher than the rate derived from the paleoseismic data (~ 1-2 mm/yr).

Two different on strike-dislocations were employed with uniform dip-slip displacements as a working model for the interseismic loading (creeping) part of the Wasatch fault. These results show that the loading rates are 5 and 6 mm/yr for the northern and southern Wasatch fault, respectively, that are about a factor of 2 to 3 higher than the geological fault-slip rate. Note that the dual-dislocation model implies higher west velocities near the fault scarp, which fits the observations better than the model with single fault patch. The improved results of using two fault segments to model the Wasatch Front horizontal velocity field suggest that multi-dislocation models with geometry similar to the fault surface traces may be plausible to describe the interseismic behavior of the Wasatch fault.

IV. Non-Technical Summary

Under the USGS National Earthquake Hazard Program, the University of Utah conducted research focused on evaluating earthquake hazards of the Wasatch Front, Utah and by operating the Wasatch Front GPS (Global Positioning Systems) network to monitor the surface deformation of the populated Wasatch Front area, Utah. High resolution GPS data, acquired by 20 continuous stations and seven field campaign surveys of ~ 60 stations, were integrated with other earthquake source data, including paleoearthquake fault-slip rates and historic seismicity, to evaluate the earthquake hazard of the Wasatch fault. Our results suggest that the Wasatch Front area has notably higher ground deformation rates than expected from the Quaternary fault data and is interpreted to relate to fault-loading processes of the Wasatch fault and surrounding structures. This increases the earthquake hazard from previous estimates. The University of Utah GPS data of seven stations are automatically sent to the University Navigation Consortium (UNAVCO) archive on a daily basis and accessible to any user over the Internet in near-real time and our research results are provided to any user via the web.

V. Meeting Participations – We presented invited and contributed papers on our research at the: 1) the 2004 Fall Meetings of the American Geophysical Union, 2) the 2005 EarthScope meeting, and 3) the 2005 annual meeting of the Geological Society of American.

VI Collaborative Efforts – We continue to work with Professor Ron Harris of Brigham Young University, Provo Utah for campaign GPS measurements. Dr. Harris has four Trimble GPS receivers that he loans to us when needed. Moreover, he supervises a team of undergraduate students that conduct campaign GPS surveys of the Wasatch fault in 2003 to our specifications costing us only their salaries and travel. This cooperative effort has materially contributed to this project.

VII. Papers, Presentations, Dissertations, etc. Related To Project (2004-2005)

Blume, F., G. Anderson, JT Freymueller, TA Herring, T.I. Melbourne, W. H. Prescott, R. B. Smith and B. Wernicke, 2004, The PBO Nucleus: Integration of the existing continuous GPS networks in the western U.S., in 2004, Eos, Transactions Amer. Geoph. Un., 2004 Fall Meeting, Suppl. Abst. G21A-0133.

Chang, W. L. and R. B. Smith, 2004. Integrated earthquake hazard of the Wasatch Front from GPS measurements ad elastic-viscoelastic fault modeling, *Programs and Abstracts, Basin and Range Province Seismic Hazards Summit II, Western States Seismic Policy Council*, 73-76.

Chang, W., and R.B. Smith, 2004, Postseismic and Interseismic Deformation of Large Normal-Faulting Earthquakes in the Basin-Range, in 2004, Eos, Transactions Amer. Geoph. Un., 2003 Fall Meeting, Suppl. Abst. G13A-0797.

Chang, W. L. and R. B. Smith, 2005. Lithospheric rheology from postseismic deformation of a M=7.5 normal-faulting earthquake with implications for continental kinematics, submitted to *J. Geophys. Res.*.

Chang, W. L. and R. B. Smith, 2005. Lithospheric rheology from postseismic deformation of a M=7.5 normal-faulting earthquake with implications for continental kinematics, *Abstracts with Programs, 111th Ann. Meeting and Exposition, Geol. Soc. Am.*, **37**, 497.

Chang, W. L. and R. B. Smith, 2004. Postseismic and interseismic deformation of large normal-faulting earthquakes in the Basin-Range, *Eos. Trans. AGU* **85**, F537.

Smith, R. B., 2004, Earthquake Hazards of the Eastern Basin-Range Province, presented at the September 2004 SESAC (Scientific Earthquake Studies Advisory Committee of the USGS) meetings, Jackson, Wyoming.

Smith, R. B., 2005, Kinematic and Dynamic Models of Western U.S. Plate Boundary Deformation, Hamilton Visiting Scholar Lecture, Southern Methodist University, Printed Scholar Schedule, Feb. 22. 2005.

VII. Availability of University of Utah GPS Data and Deformation Products

All University of Utah continuous GPS observed data are available to the interested user and public in near real-time via the Internet. The data are downloaded daily and archived in Rinex format the UNAVCO (University NAVSTAR consortium) data management center, Boulder, Colorado at http://www.unavco.org/query/pss.

University of Utah processed GPS data are posted on our website at http://www.mines.utah.edu/~ggcmpsem/UUSATRG/GPS/time_series.html

Interpretative level research products including ground motion vectors, error analyses, etc. are available on our website http://www.mines.utah.edu/~rbsmith/RESEARCH/UUGPS.html

An important local user component of our research project provides the surveying community with our data for survey referencing with access to our data via the UNAVCO data web site above.

In addition, hourly data from the RBUT station are provided to the National Geodetic Survey and contribute to the NGS CORS on-line network that are accessible by ftp at ftp://cors.ngs.noaa.gov/coord.

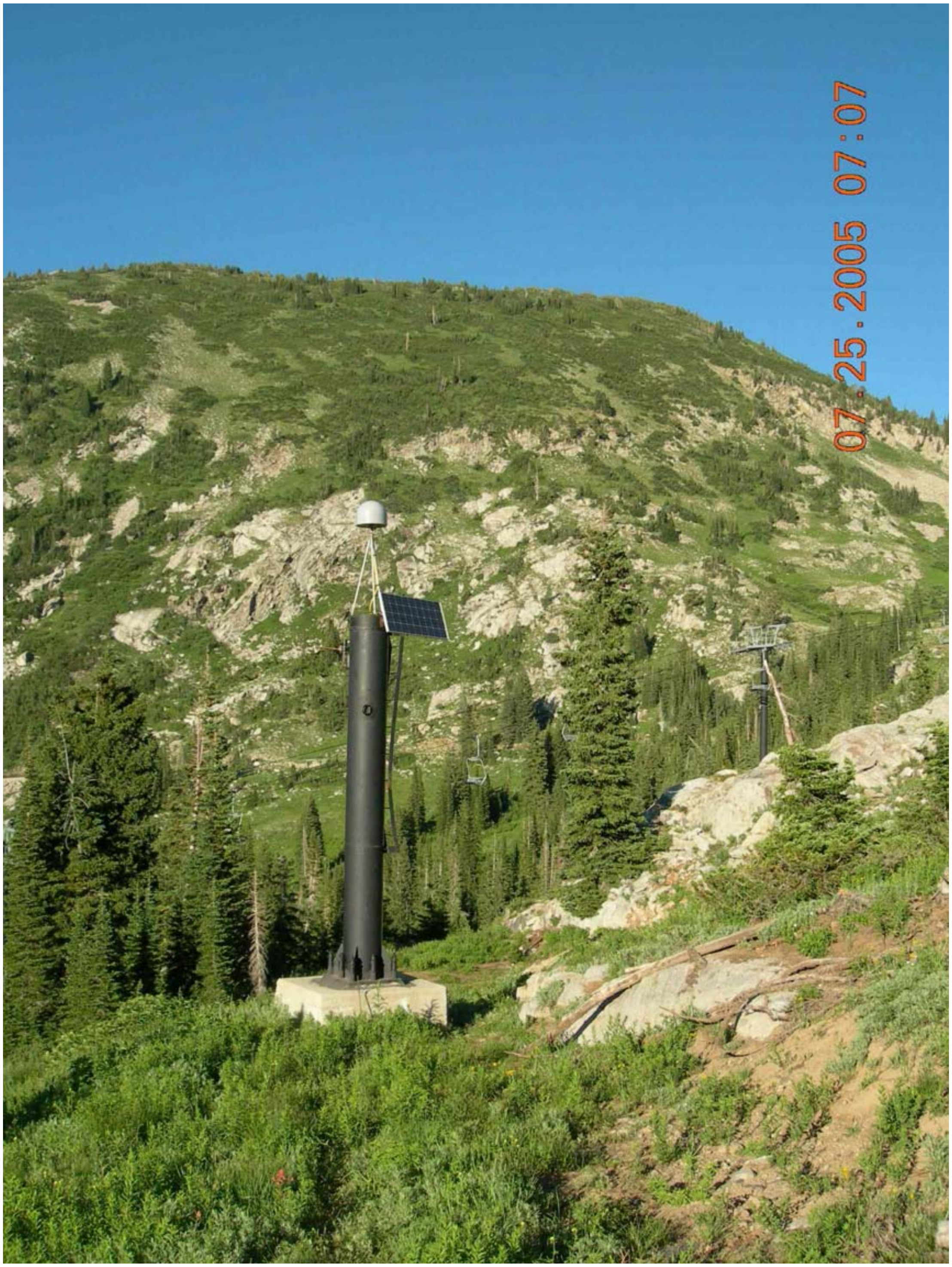

Figure 1. Picture of new GPS site at Alta (Albion Basin) Utah. Data are transmitted to the town of Alta municipal building via spread-spectrum radio and relayed to the University of Utah.

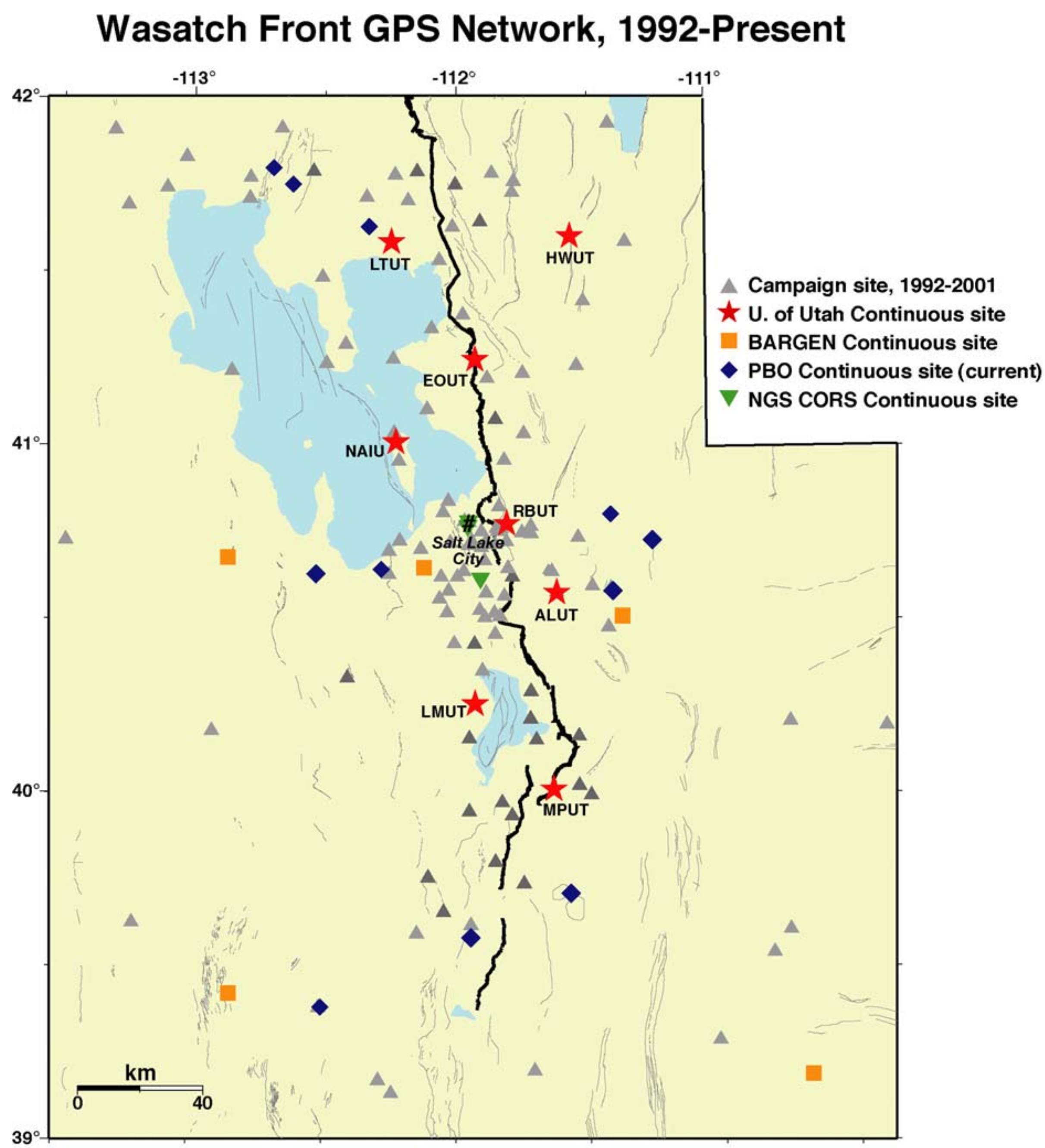

Figure 2. Continuous and campaign GPS stations of the Wasatch Front, Utah. Thick black lines highlight the Wasatch fault.

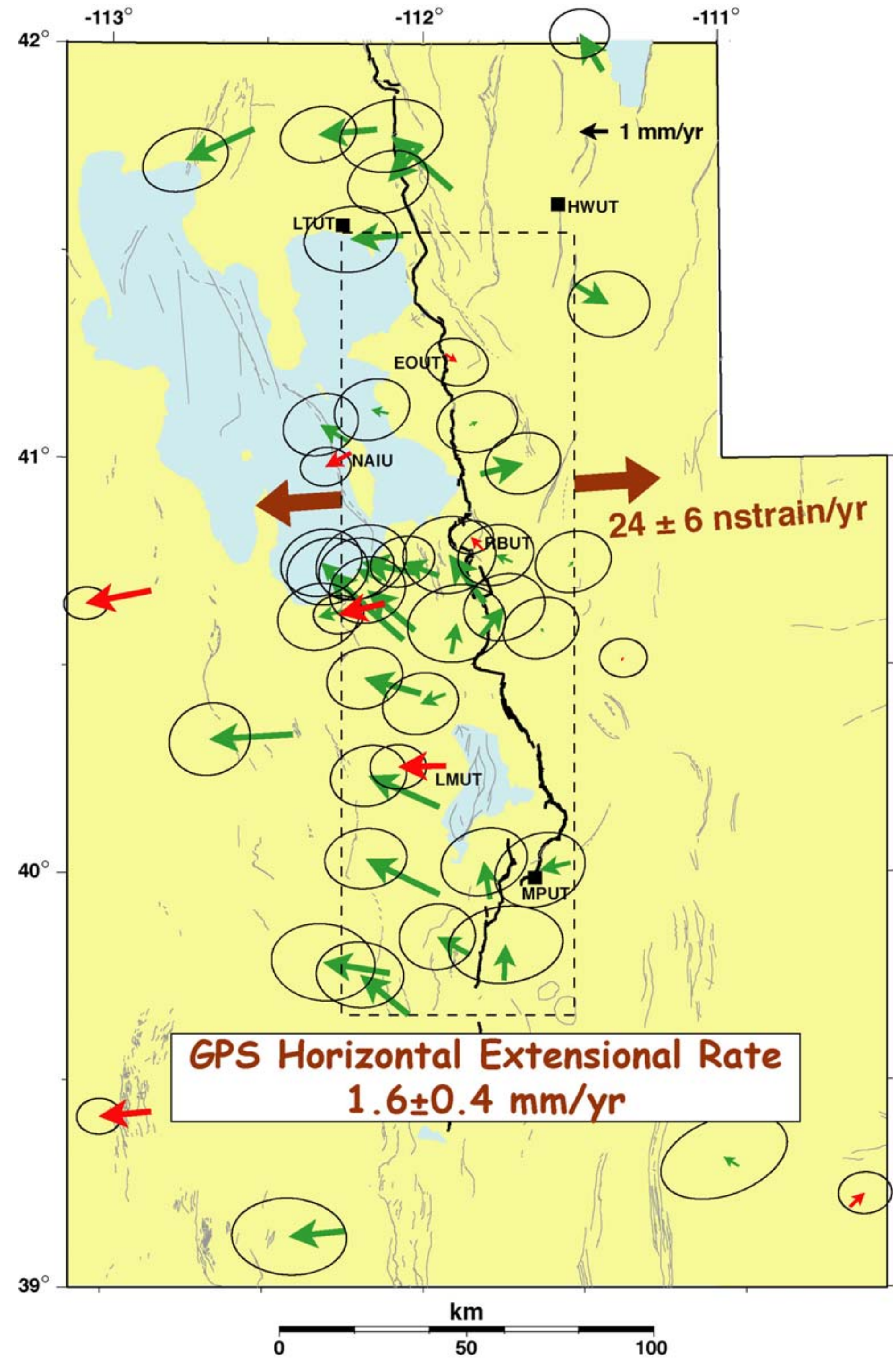

Figure 3. Horizontal velocity vectors in a stable North America reference frame derived from the 1997-2005 continuous (red) and 1992-2001 campaign (green) GPS observations. Error ellipses represent the 95% confident intervals. Spatially homogeneous strain rate (dashed box) across the Wasatch fault is shown by brown arrows.

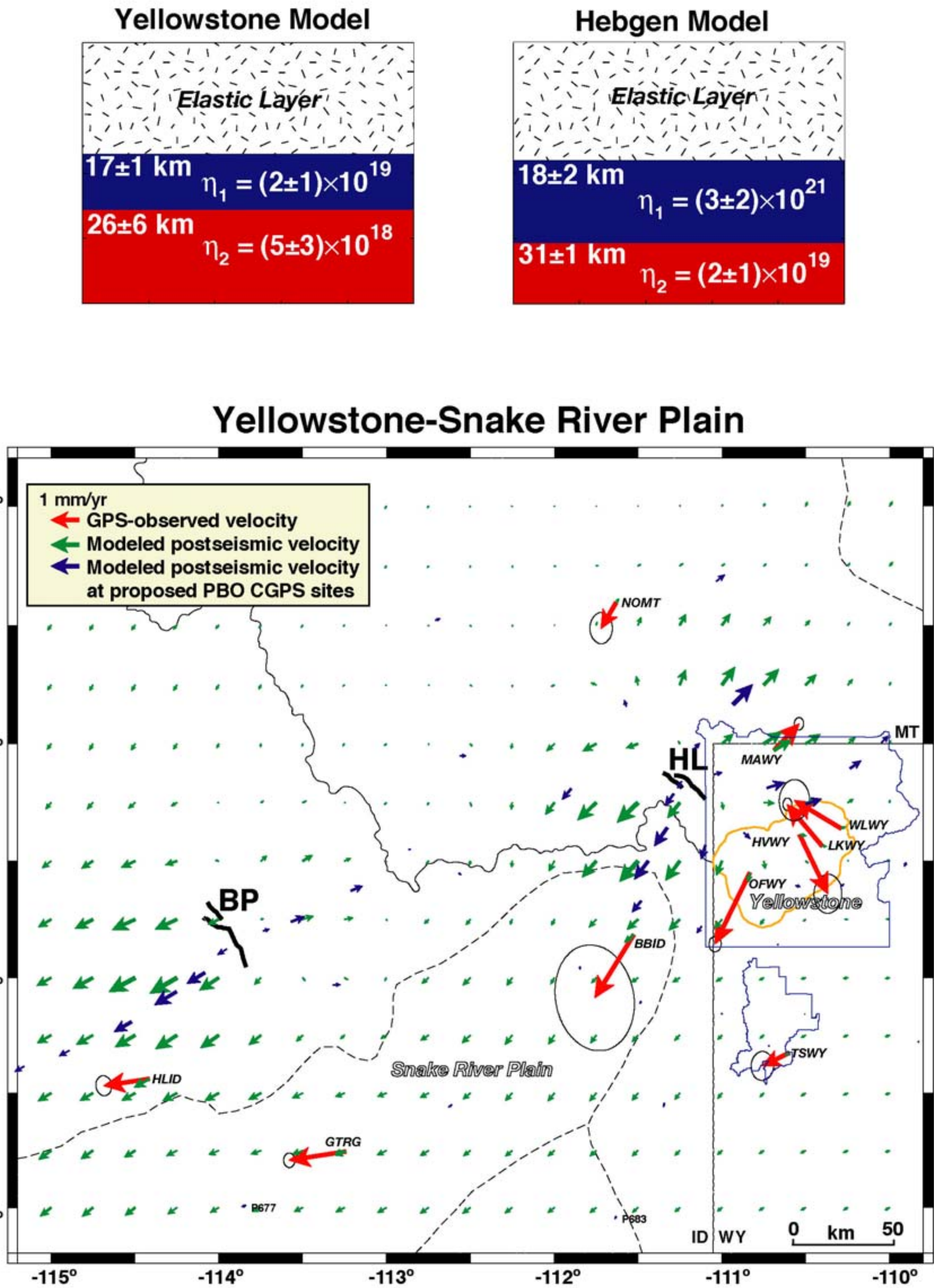

Figure 4. Top: two best-fit rheological models derived from the postseismic deformation of the 1959 Hebgen Lake, MT, earthquake. Bottom: modeled horizontal postseismic velocities (green and blue arrows) in the Yellowstone-Snake River Plain region caused by the Hebgen Lake (HL) and Borah Peak (BP) earthquakes. HEBGEN model was employed for the rheologic structure.

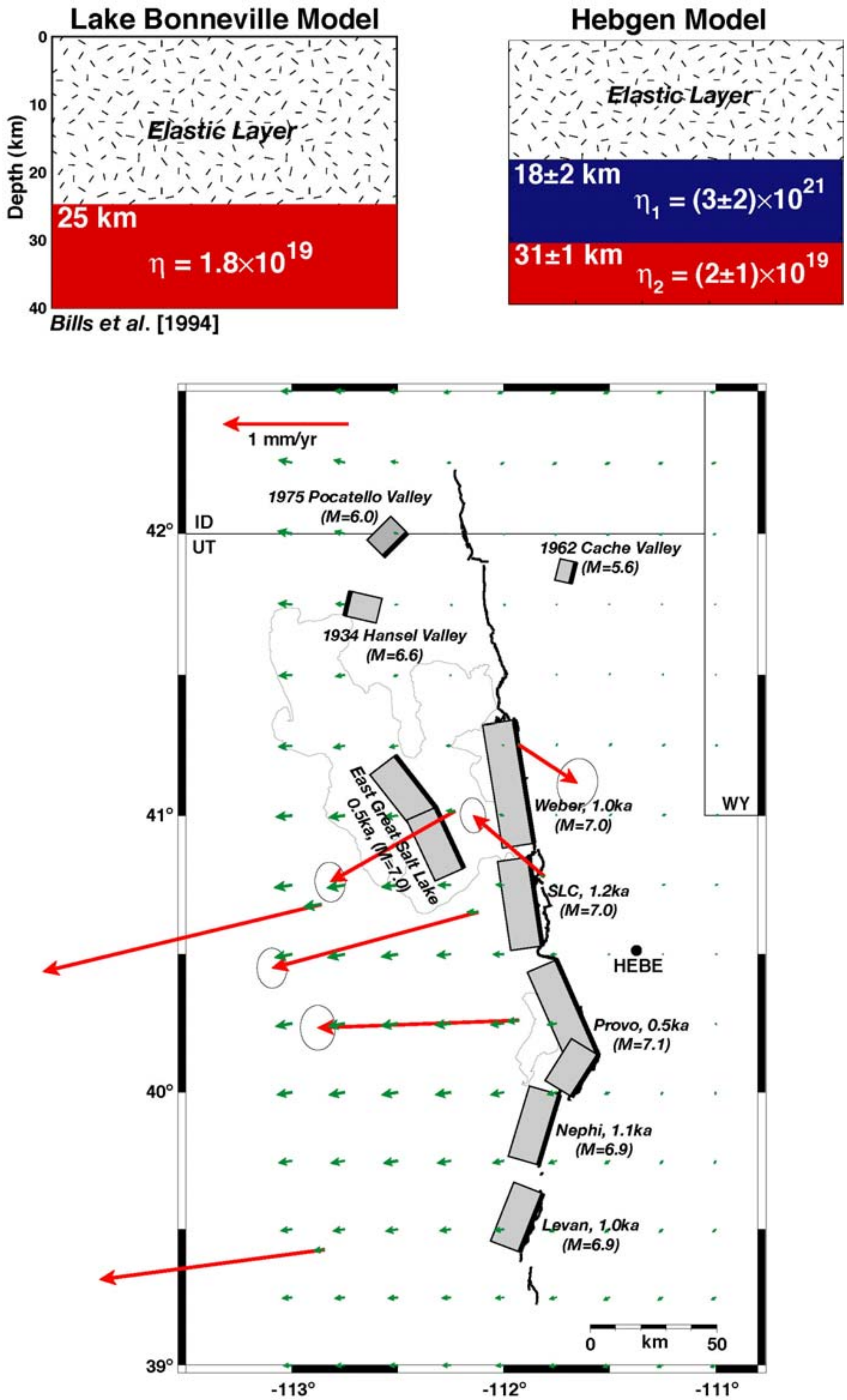

Figure 5. Horizontal velocities of the Wasatch Front, Utah, from modeled postseismic response (green arrows) and the contemporary deformation observed from the permanent GPS stations (red arrows). This shows that the paleo- and historic earthquakes have a negligible effect on the contemporary strain field of the Wasatch fault. Fault dislocation models for six paleoearthquakes and three historic events are shown by gray rectangles. Black lines highlight the Wasatch fault.